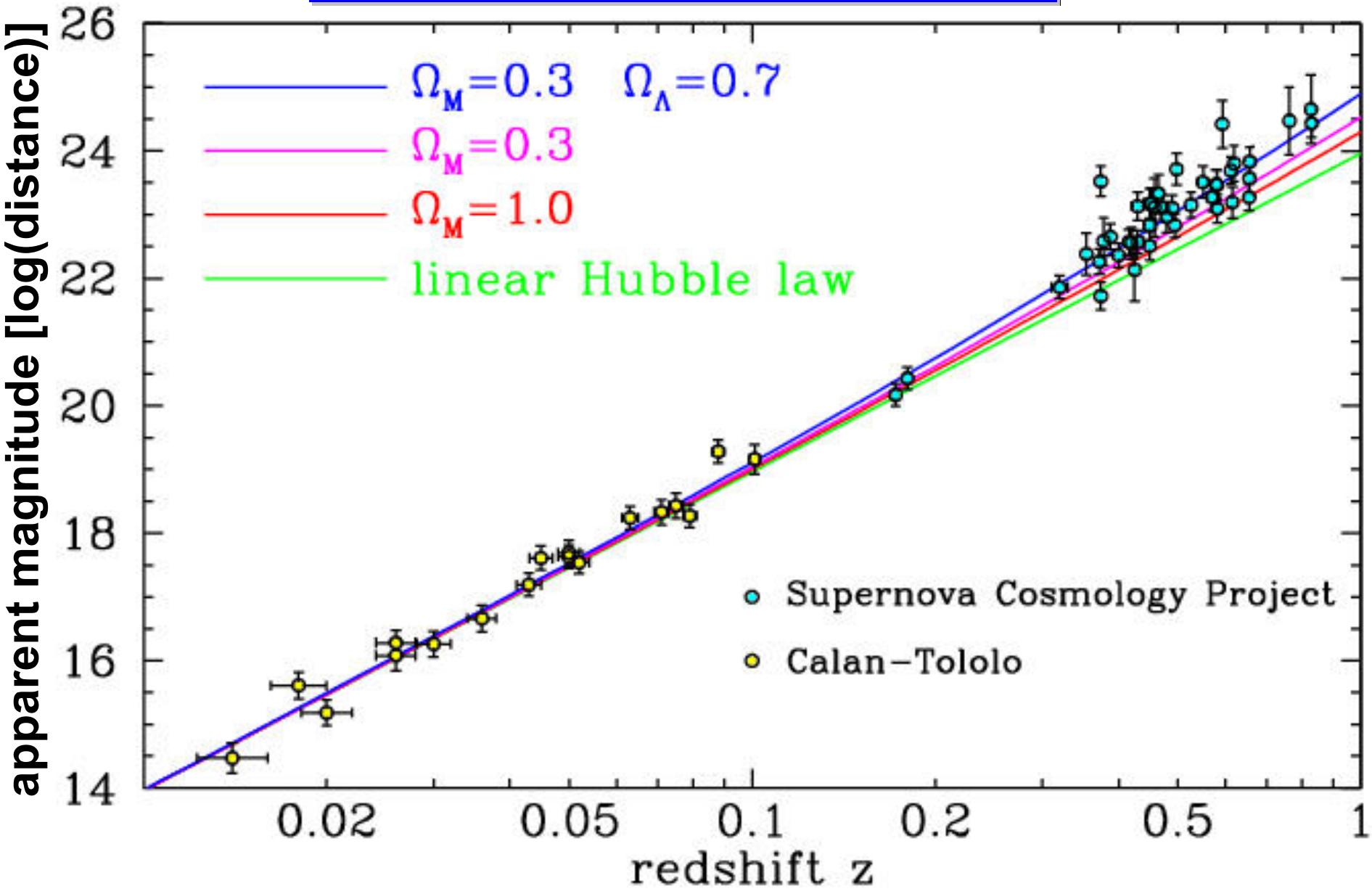
Cosmology and the origin of structure

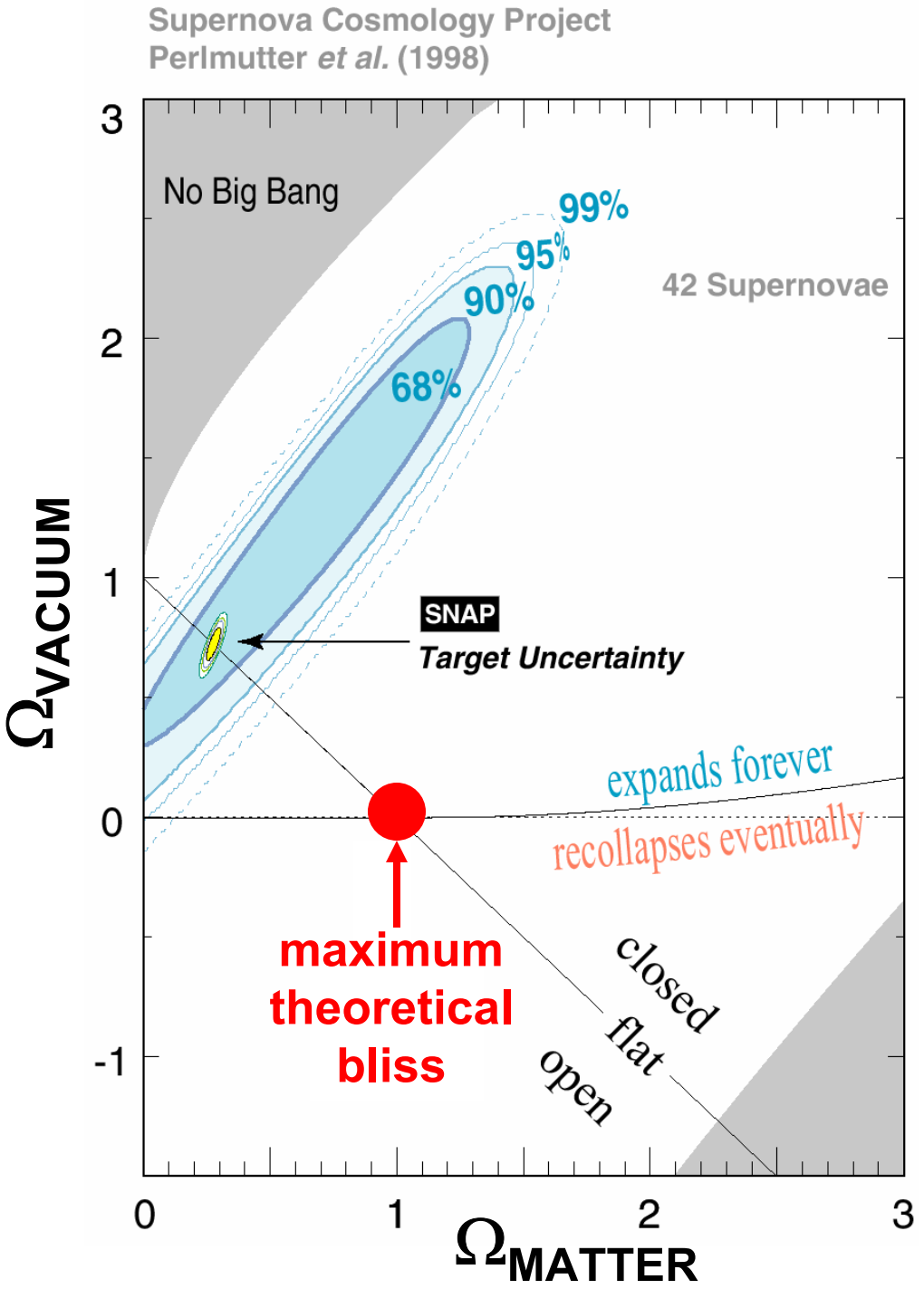
Rocky I: Dark Energy

Rocky II: Dark Matter

Rocky Kolb
Fermilab & The University of Chicago

Type Ia supernova





High-z SNeIa are fainter than expected in an Einstein-deSitter model

cosmological constant, or …some changing non-zero vacuum energy, or … or some unknown systematic effect(s)

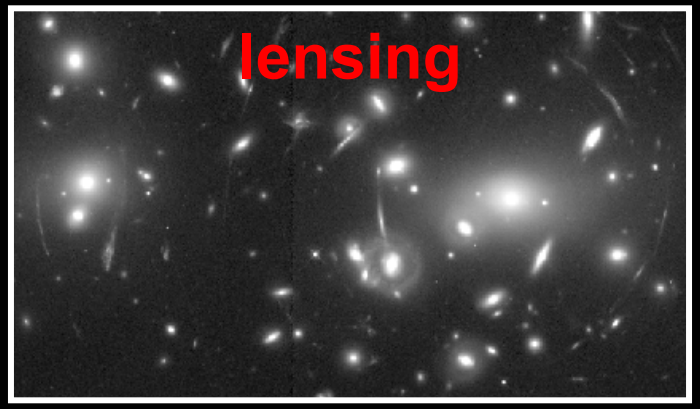
<u>The case for Λ:</u>

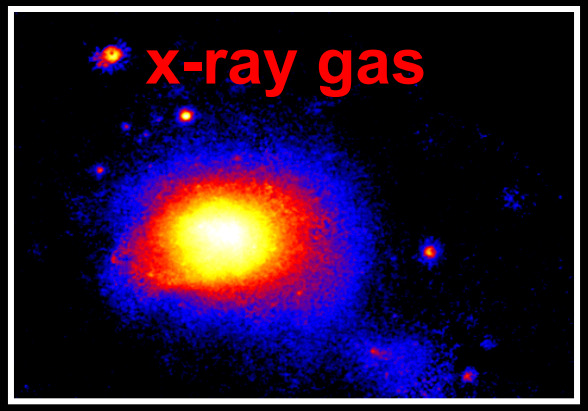
1) Hubble diagram

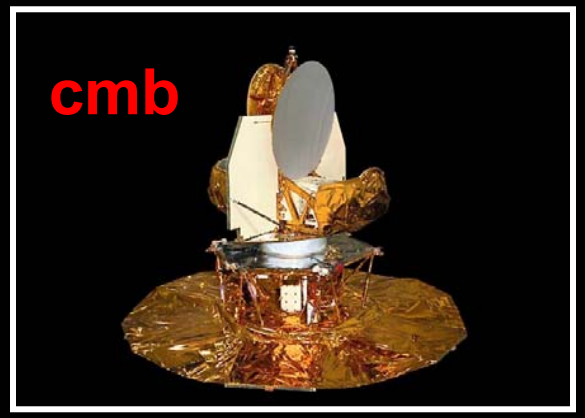
2) subtraction

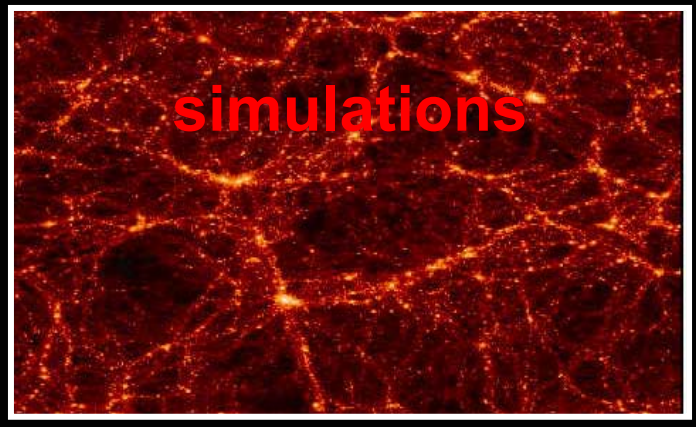
$\Omega_{MATTER} \sim 0.3$

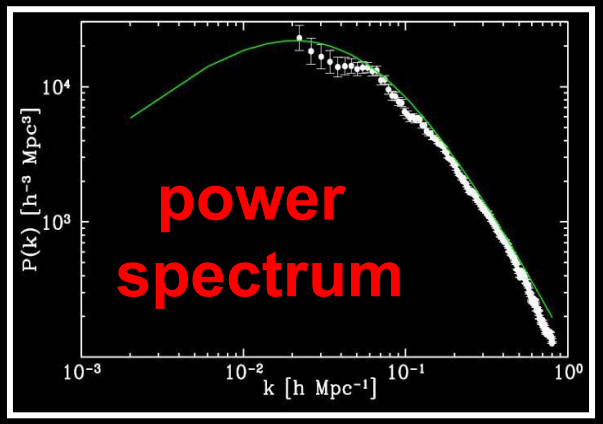
$\Omega_{TOTAL} = 1$





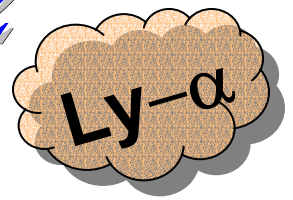


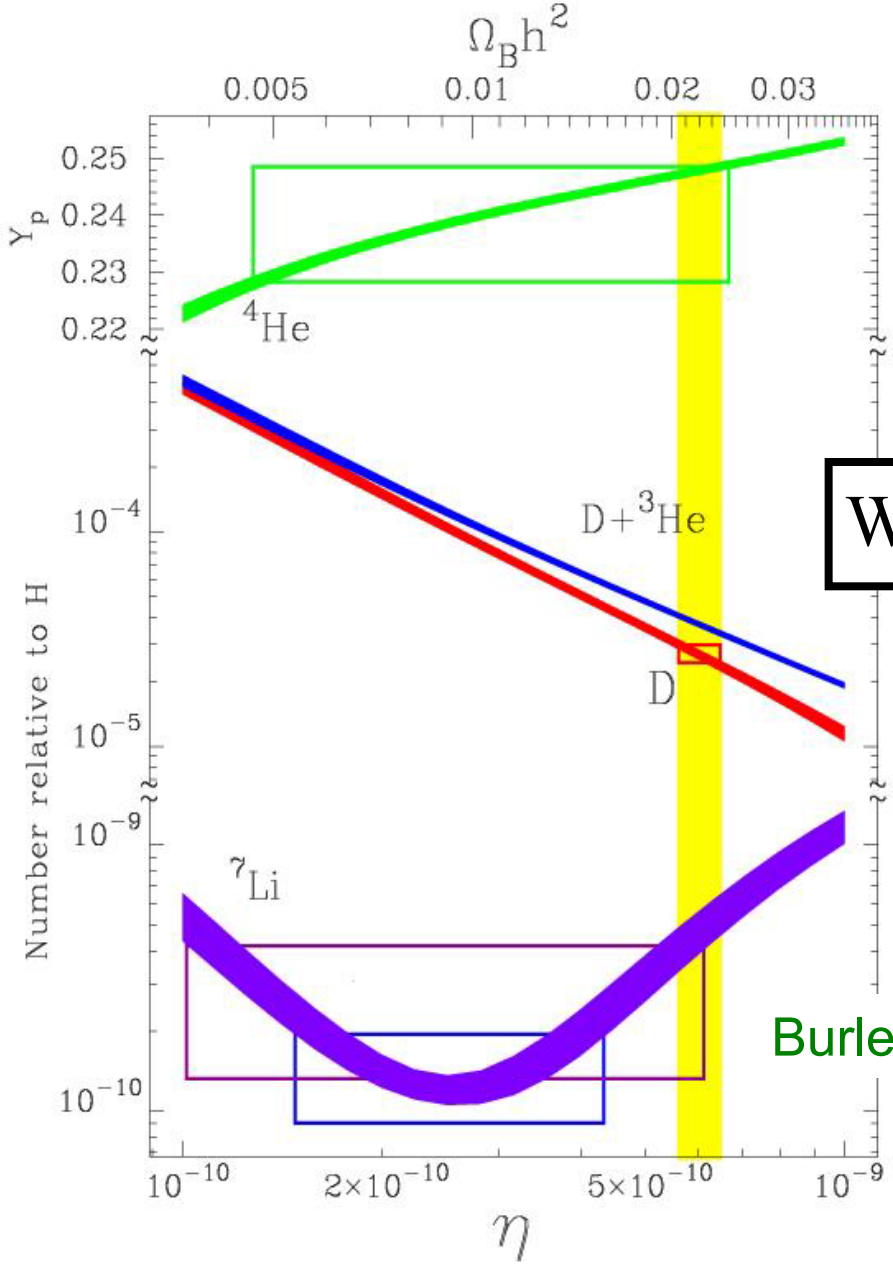




$1 - 0.3 = 0.7$

Baryons $\Omega_B h^2 \sim 0.02$

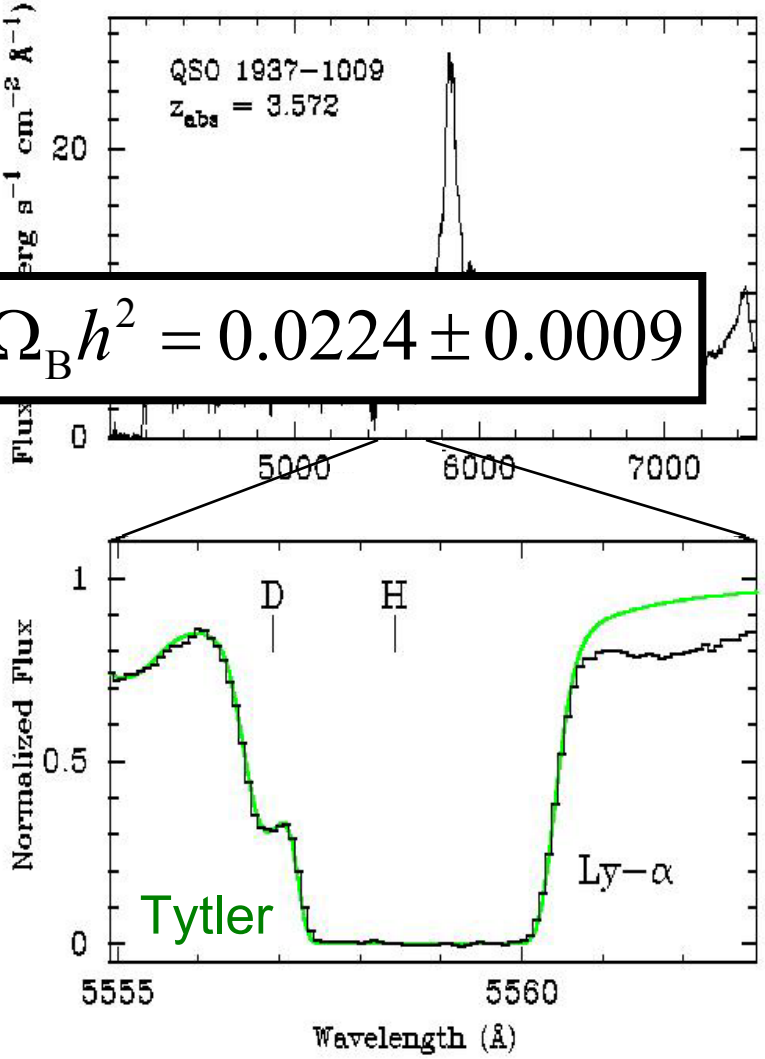


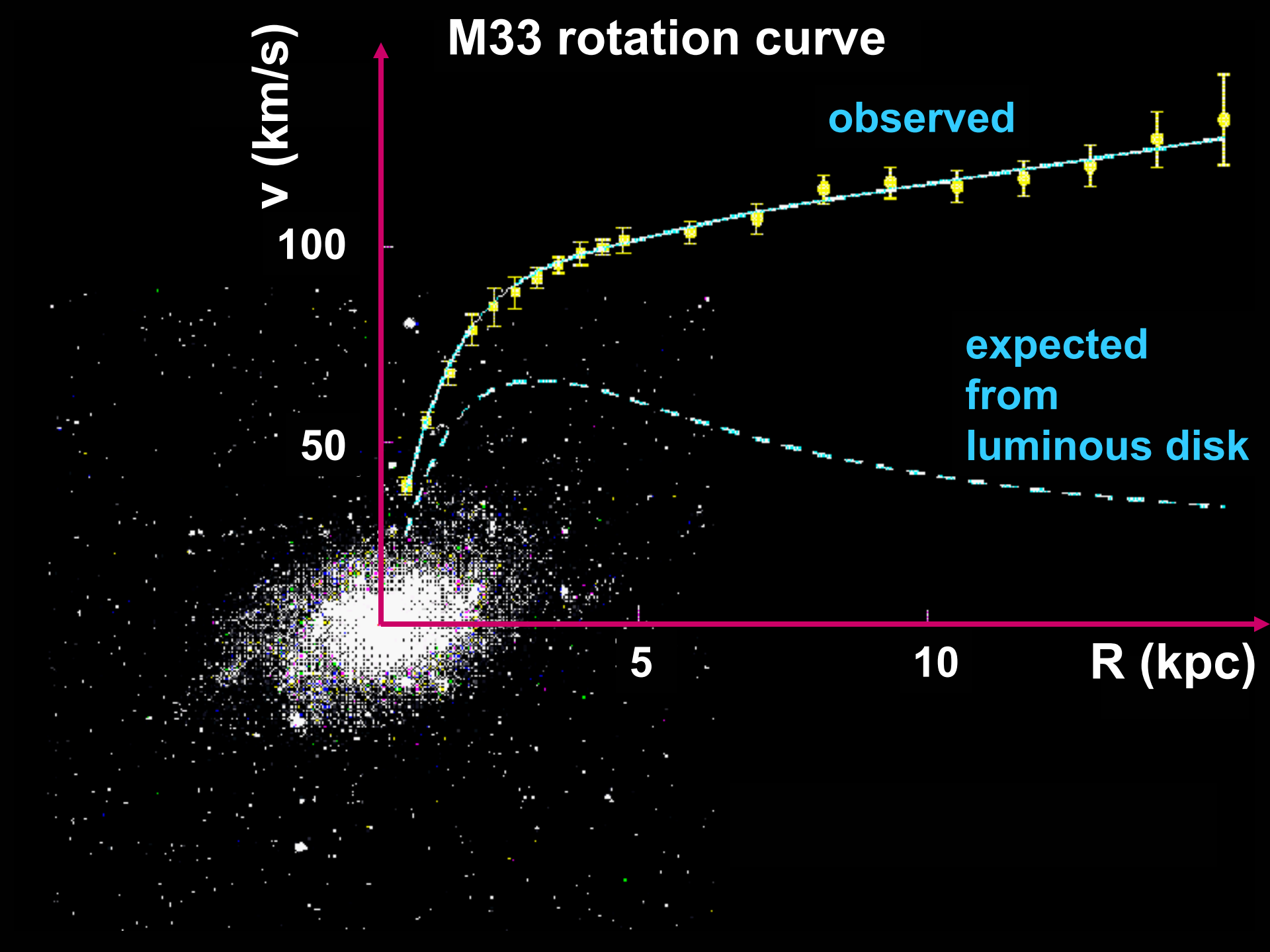


Burles et al.

$$\text{WMAP: } \Omega_B h^2 = 0.0224 \pm 0.0009$$

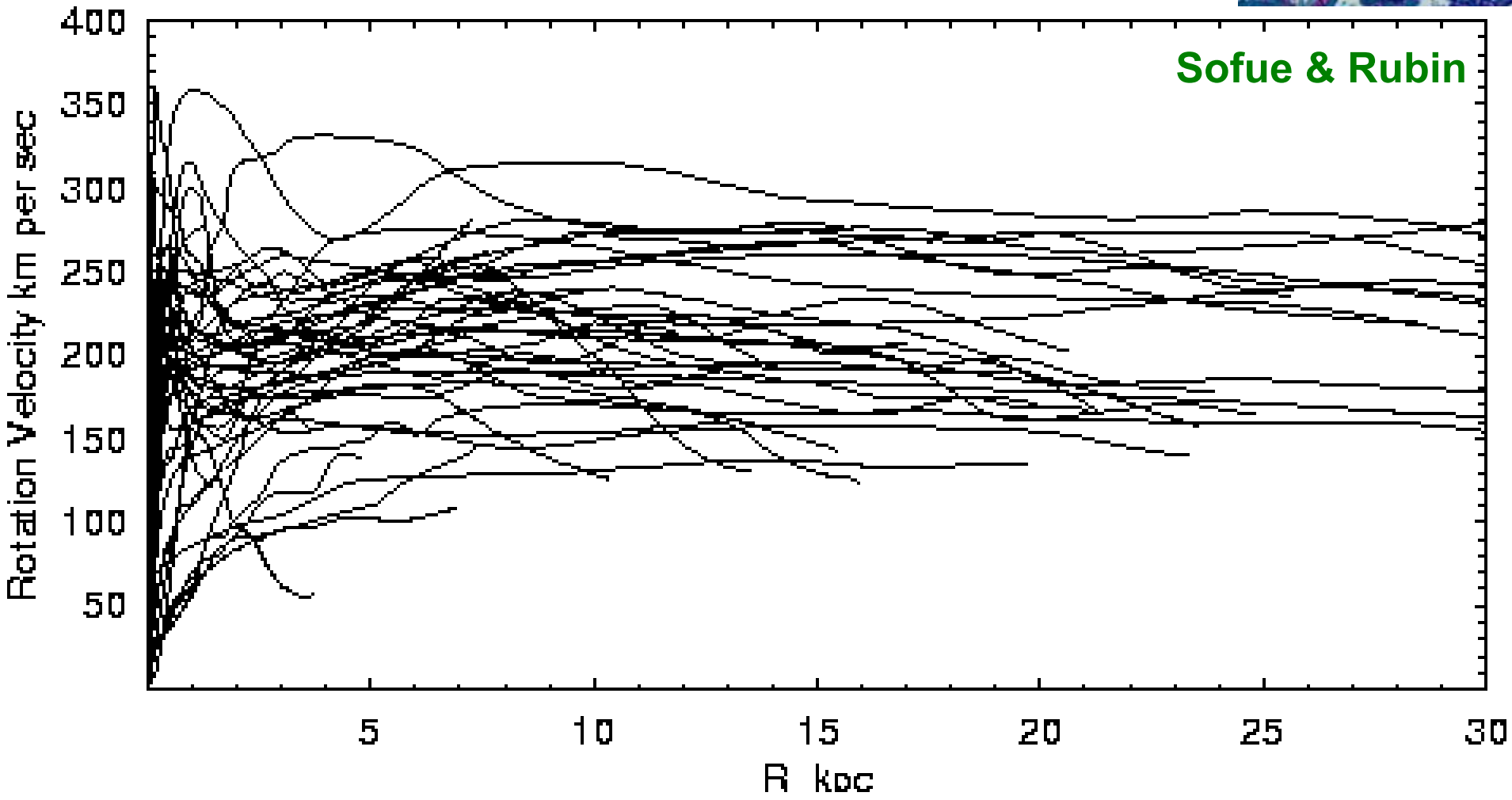
QSO 1937-1009




M33 rotation curve
v (km/s)
100
50
observed
expected
from
luminous disk
5
10
R (kpc)

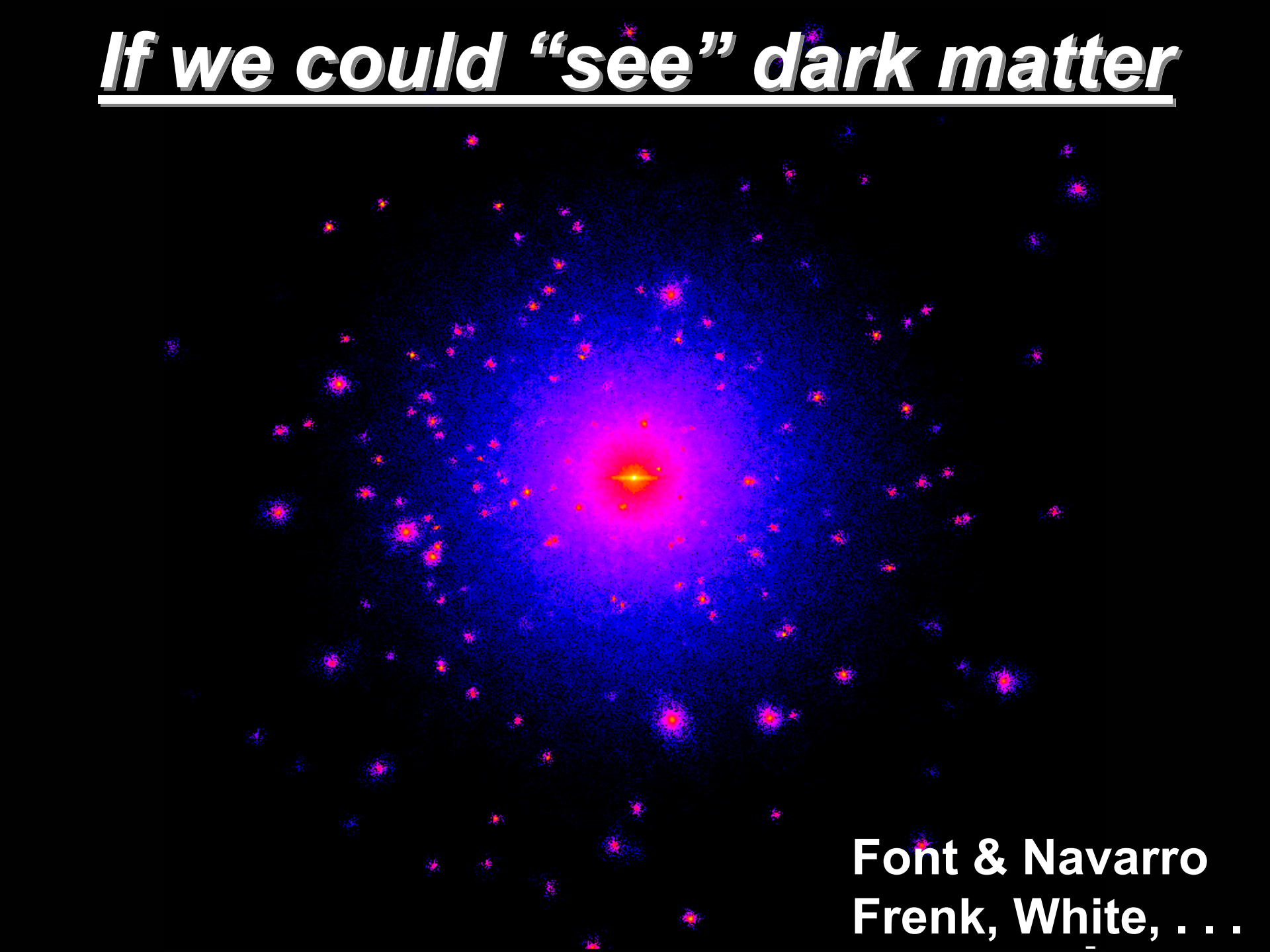
Rotation curves

CO – central regions
Optical – disks
HI – outer disk & halo

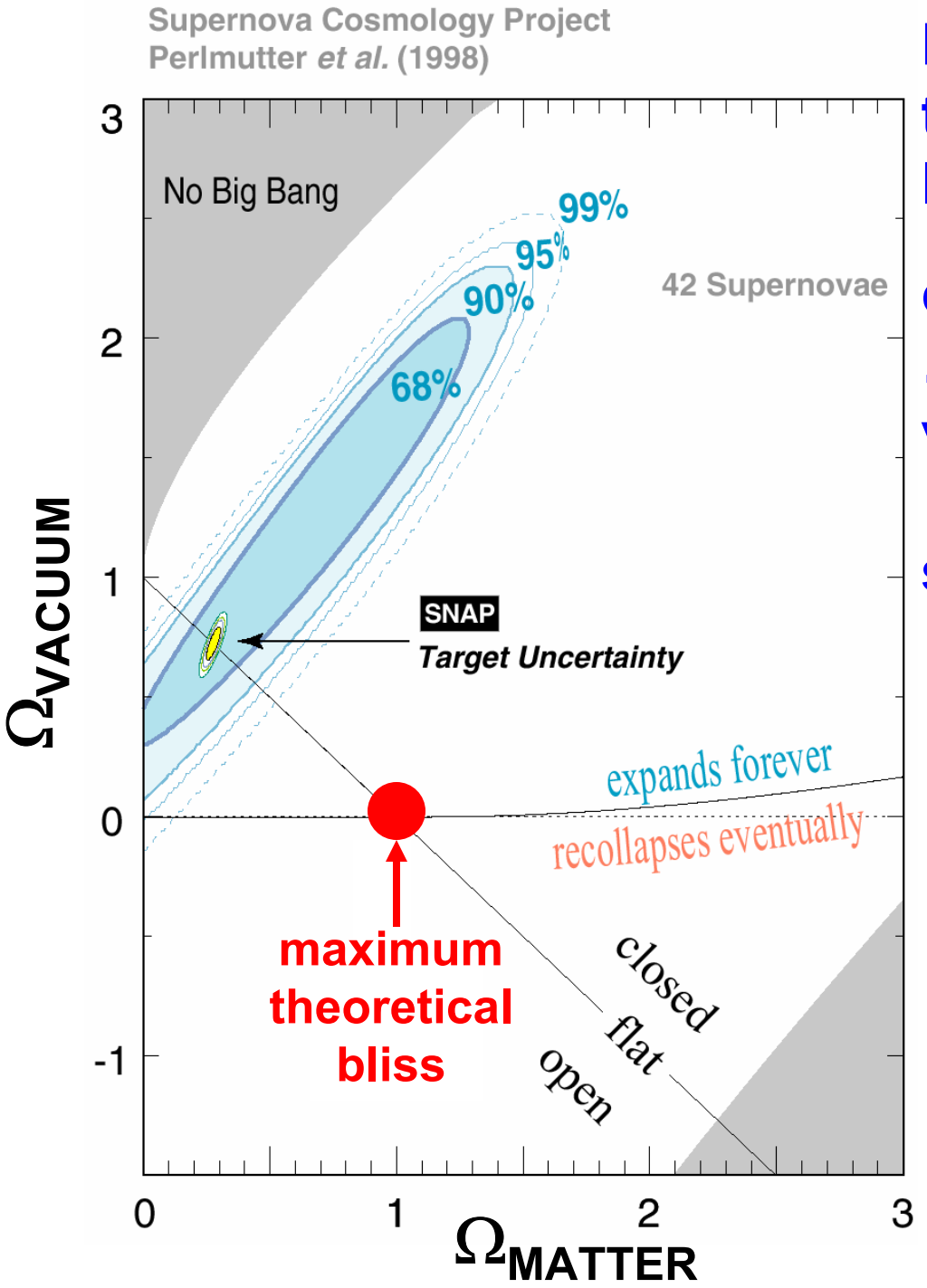


Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope • WFPC2

If we could "see" dark matter



Font & Navarro
Frenk, White, . . .



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cosmological constant, or
…some changing non-zero vacuum energy, or
… or some unknown systematic effect(s)

The case for Λ:

1) Hubble diagram

2) subtraction

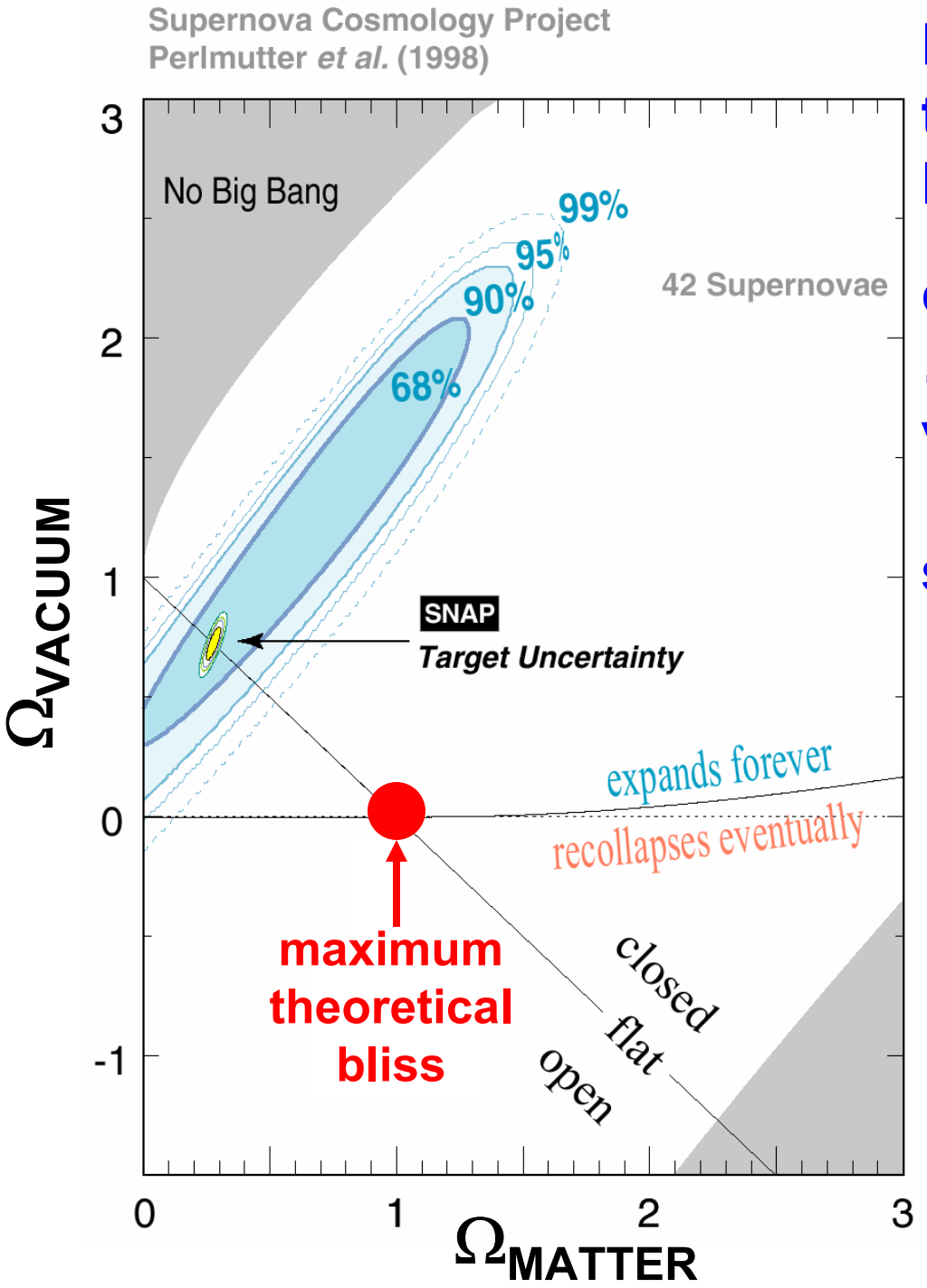
$\Omega_{TOTAL} = 1$
$\Omega_M = 0.3$
$1 - 0.3 = 0.7$

3) age of the universe

t_0 : age of the universe

- white dwarf cooling 11 ± 2 Gyr
- nucleocosmochronology 12.6 ± 3 Gyr
- globular cluster evolution 13.5 ± 2 Gyr

H_0 =70	Ω_M	Ω_Λ	t_0 (Gyr)
Flat	1.0	0	9.3
Open	0.3	0	12
Open	0.2	0	14
Flat	0.3	0.7	13.5
Flat	0.2	0.8	15



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The case for Λ:

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$\Omega_{TOTAL} = 1$
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3) age of the universe

4) structure formation

Einstein's Biggest Blunder?

1917 Einstein proposes cosmological constant

1929 Hubble discovers Expansion of the universe

1934 Einstein calls it "my biggest blunder"

1998 Astronomers find evidence for it

Λ

Field equation: $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$

Perfect fluid stress tensor: $T^{\mu}{}_{\nu} = \mathrm{diag}\left(\rho, -p, -p, -p\right)$

"I found it very ugly indeed that the field law of gravitation should be composed of two logically independent terms connected by addition. About the justification of such feelings concerning logical simplicity it is difficult to argue. I cannot help to feel it strongly and I am unable to believe that such an ugly thing should be realized in nature."

Einstein in a letter to Lemaitre, Sept. 26, 1947

Modern view: "It belongs on the right-hand side, and has many contributions."

$$\tilde{T}^{\mu}{}_{\nu} = \mathrm{diag}\left(\rho_\Lambda, \rho_\Lambda, \rho_\Lambda, \rho_\Lambda\right) \qquad \rho_\Lambda = \Lambda / 8\pi G$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \left(T_{\mu\nu} + \tilde{T}_{\mu\nu}\right)$$

Cosmological constant

Mass density of space:

$$\rho_\Lambda \simeq 10^{-30}\,\mathrm{g\,cm^{-3}} \simeq \left(10^{-4}\ \mathrm{eV}\right)^4 = \left(10^{-3}\ \mathrm{cm}\right)^{-4}$$

$$\Lambda = 8\pi G\rho_\Lambda = \left(10^{29}\,\mathrm{cm}\right)^{-2} = \left(10^{-33}\,\mathrm{eV}\right)^2$$

The unbearable lightness of nothing!

Cosmo-illogical constant?

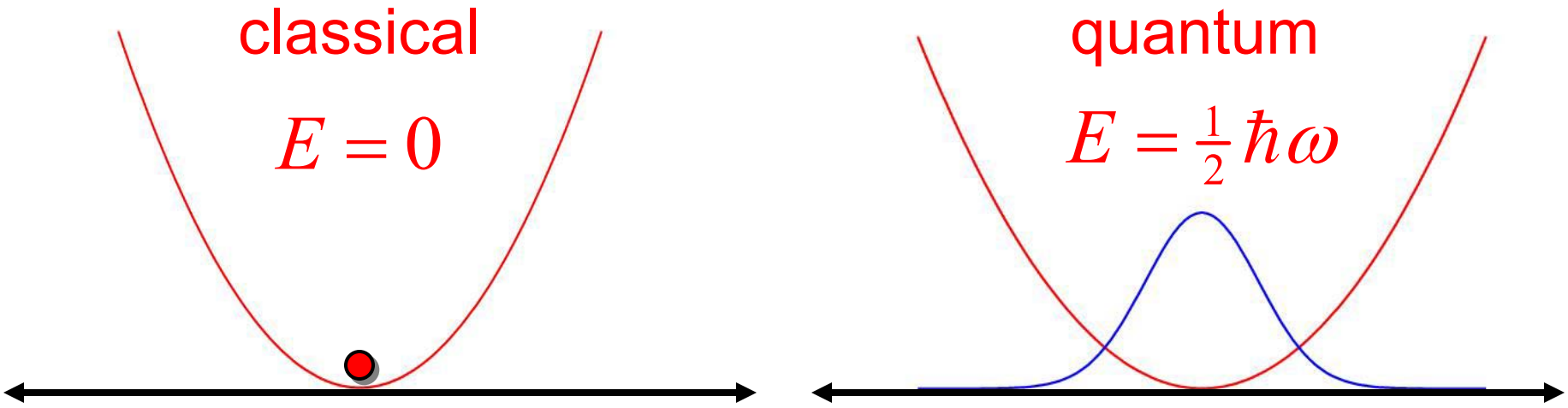
Numerology:

$$\rho_V = M_W^4 \exp\left(-2/\alpha\right) \qquad \rho_V = M_{\mathrm{SUSY}}^8 \Big/ M_{Pl}^4$$

$$m_\nu = 10^{-3}\ \mathrm{eV} \qquad R_5 = 10^{-4}\ \mathrm{cm}$$

Quantum uncertainty

Fourier modes of all fields are harmonic oscillators with a zero-point energy



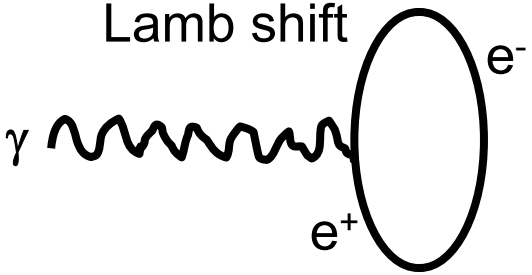
$$\rho = \sum_{\text{all particles}} \pm \int d^3k \sqrt{k^2 + m^2}$$

Quantum uncertainty

$$\rho = \sum_{all\ particles} \pm \int d^3k \sqrt{k^2 + m^2} \simeq \sum_{all\ particles} \pm \int^{\Lambda_C} d^3k\ k^4$$

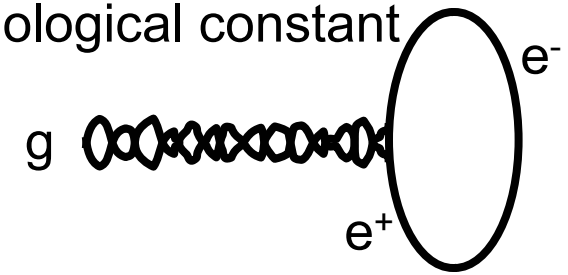
Photons couple to virtual particles

Lamb shift



Gravitons couple to virtual particles

Cosmological constant



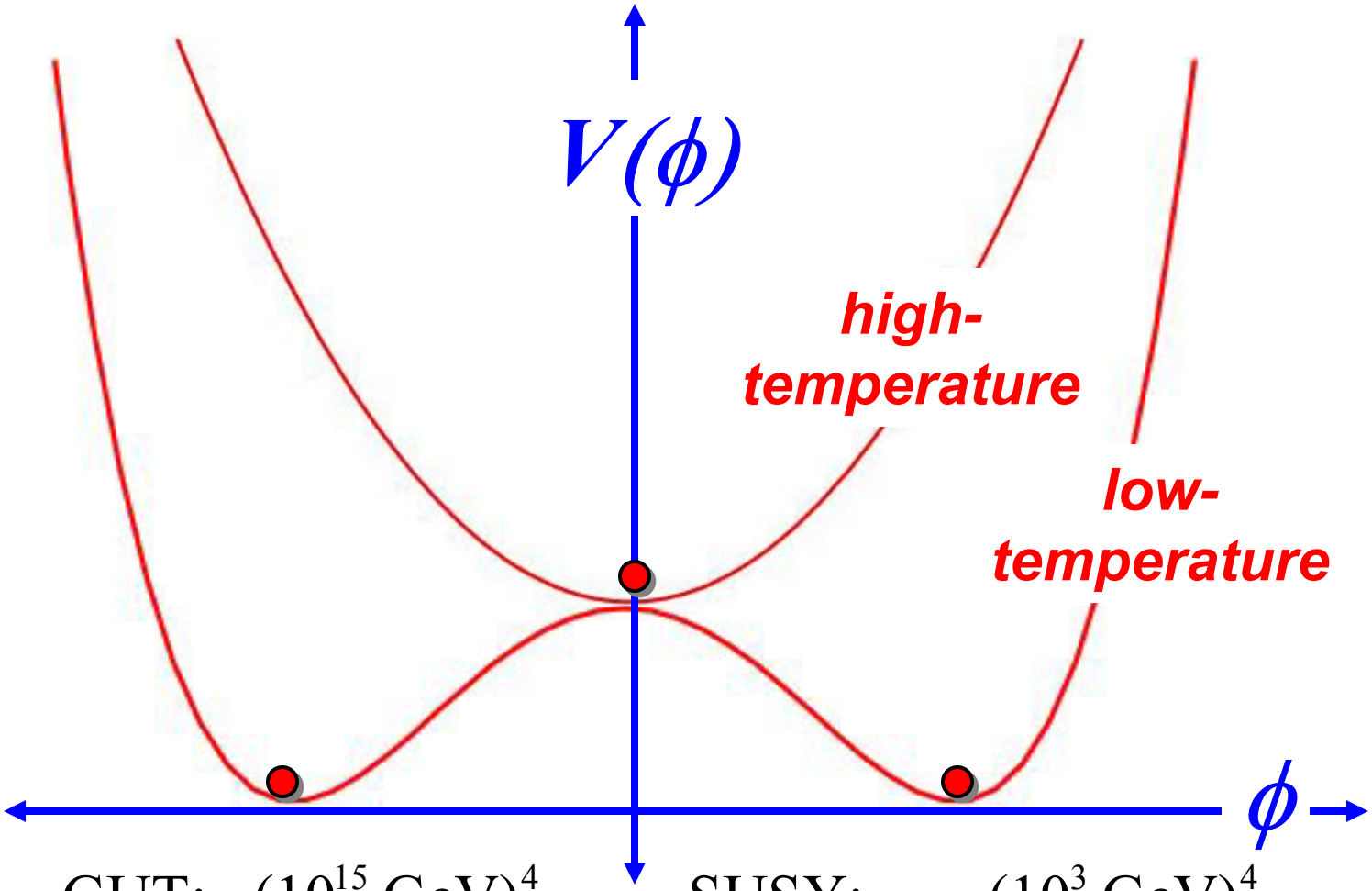
$$\Lambda_C = \infty: \quad \rho_\Lambda = \infty^4 \quad = \text{bad prediction}$$

$$\Lambda_C = M_{Pl}: \quad \rho_\Lambda = M_{Pl}^4 \quad = \left(10^{28}\ \text{eV}\right)^4$$

$$\Lambda_C = M_{SUSY}: \quad \rho_\Lambda = M_{SUSY}^4 = \left(10^{12}\ \text{eV}\right)^4$$

$$\Lambda_C = 10^{-3}\,\text{eV}: \quad \rho_\Lambda = \text{Observed}$$

Spontaneous symmetry breaking



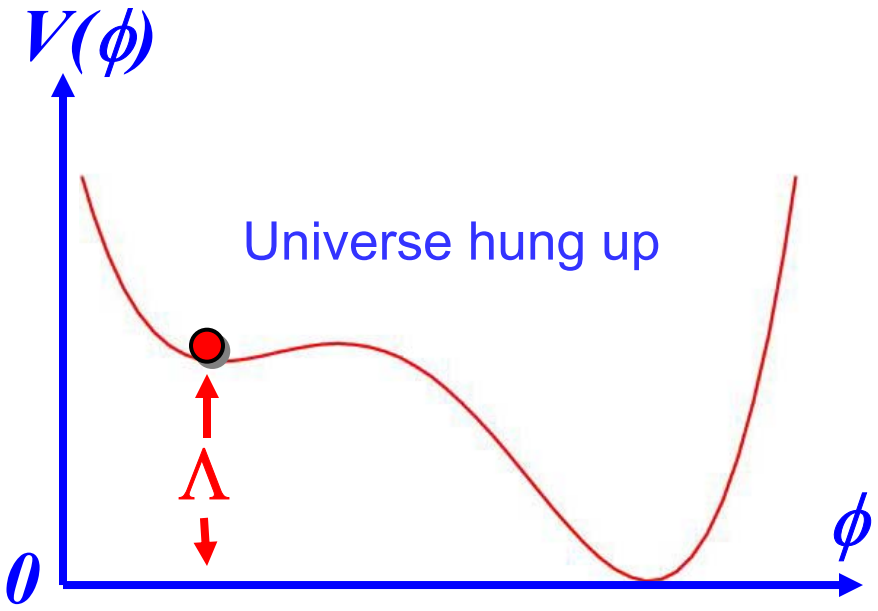
GUT: $(10^{15}\ \text{GeV})^4$ SUSY: $(10^{3}\ \text{GeV})^4$

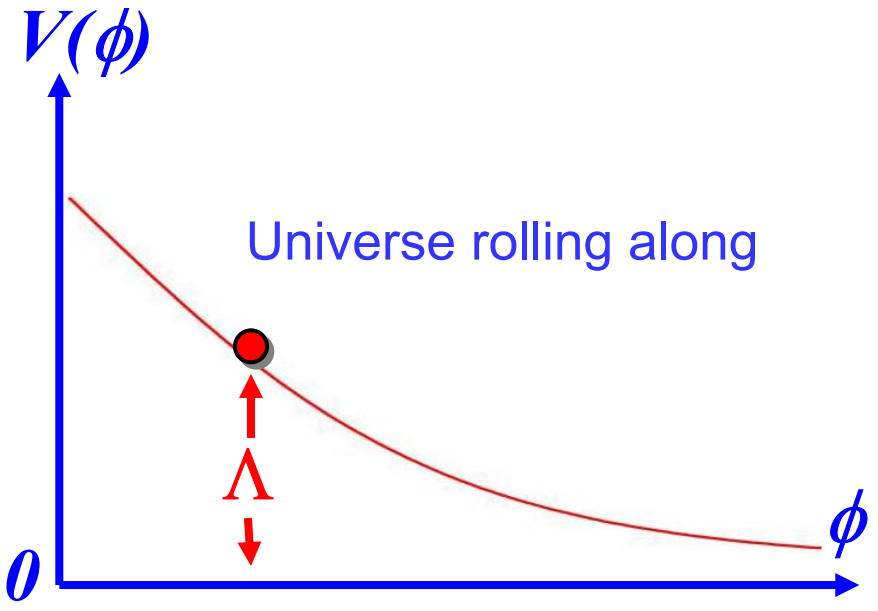
EWK: $(10^{2}\ \text{GeV})^4$ CHIRAL: $(10^{-1}\ \text{GeV})^4$

OBSERVED: $(10^{-12}\ \text{GeV})^4$

Balancing other contributions

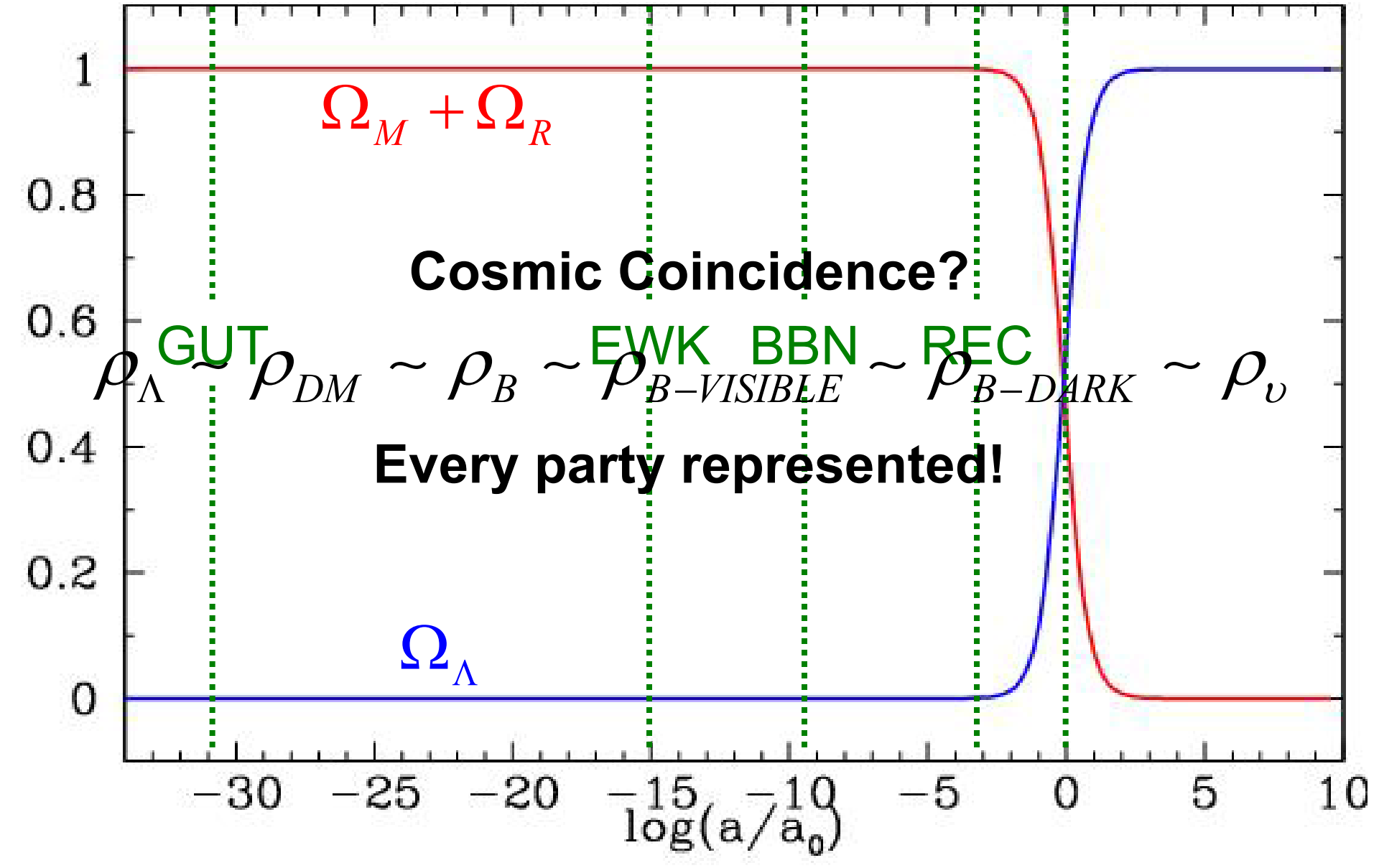
- **Many possible contributions.**
- **Why then is total so small?**
- **Perhaps unknown dynamics sets global vacuum energy equal to zero……*but we're not there yet!***





Frieman, Freese, Hill, Olinto, …..

Cosmic coincidence



Cosmic Coincidence?

$$\rho_\Lambda \sim \rho_{DM} \sim \rho_B \sim \rho_{B-VISIBLE} \sim \rho_{B-DARK} \sim \rho_\upsilon$$

GUT EWK BBN REC

Every party represented!

Λ: the uninvited guest

1. **No unbroken symmetry demands $\Lambda=0$**
2. **Nothing sets the scale**
3. **Scale seems unrelated to any other energy scale**

   . . . seems to require $m \sim 10^{-33}$ eV

   . . . fifth-force experiments?

> Non l'avrei giammai creduto;
> Ma farò quel che potrò.
>
> *Mozart/Da Ponte,*
> *Don Giovanni, Act II*

4. ***Deal with it!***

Dark energy depression?

1. Alcohol*
2. Drugs*
3. Anthropic principle*
4. Creative theories
5. Hard experimental work
6. Observational direction

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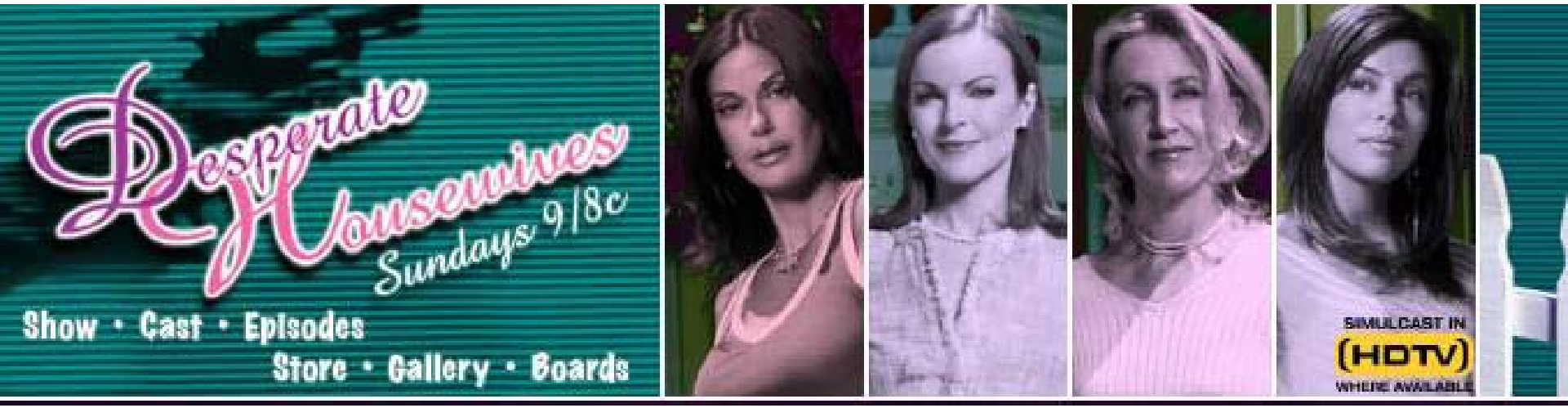
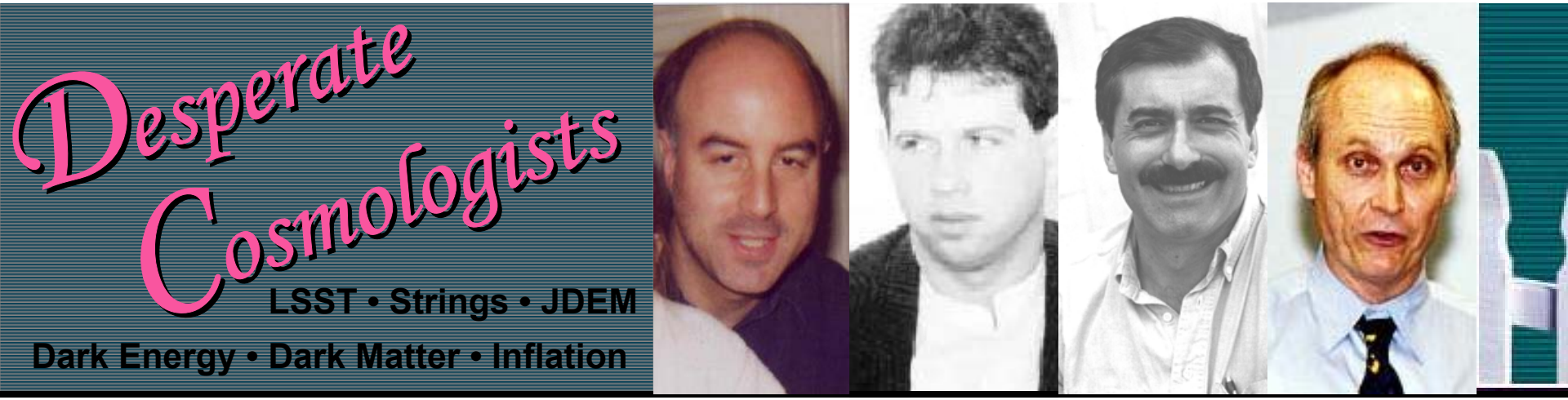
* Therapy, medication, and twelve-step programs available.

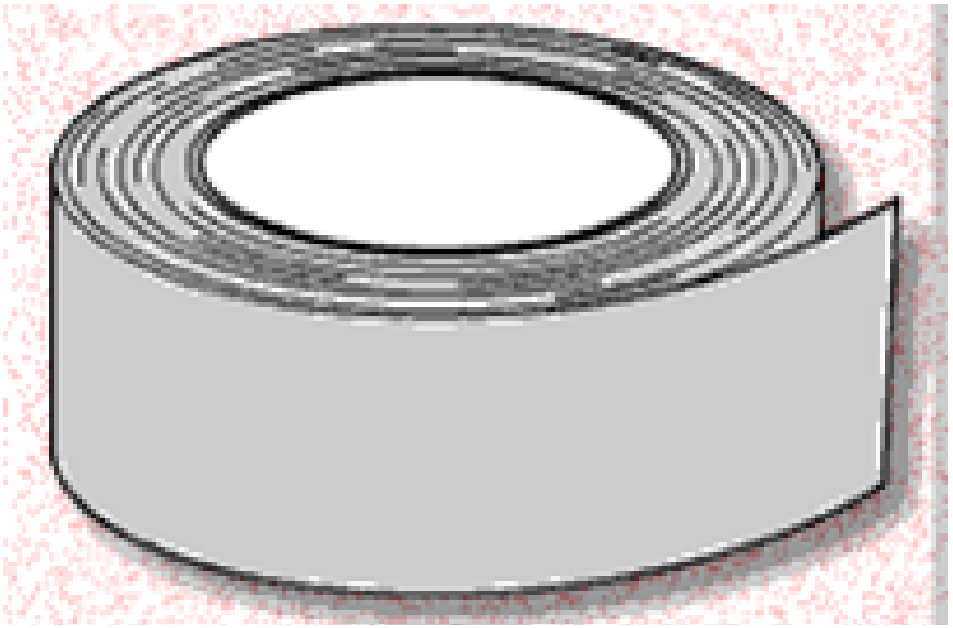


How Far Will They Go?



How Far Will They Go?

Theoretical Toolbox



anthropic principle

scalar fields

Entertaining conjecture

Now entertain conjecture of a time
When creeping murmur and the poring dark
Fills the wide vessel of the universe.

— *King Henry V*th

All evidence for dark energy (creeping murmur) is indirect!

SNIa
Age : $\int \frac{dz}{H(z)}$
LSS

- We infer dark energy from time evolution of H.
- Observed time evolution of H does not fit Einstein–de Sitter.
- We *infer* the existence of dark energy!
- Could Friedmann equation be modified?

Take sides!

- Something is established – ΛCDM too good to ignore
  - SNIa
  - Subtraction
  - Age
  - Large-scale structure
  - …

  } $H(z)$ not given by Einstein–de Sitter cosmological model

- Dark energy (right-hand side of Einstein equations)?
  - Is it "just" a cosmological constant?
  - If not cosmological constant, what is dynamics?
  - interpretation of $w = \rho/p$?

- Gravity (left-hand side of Einstein equations)?
  - Beyond Einstein (non-GR: branes,etc.)
  - (Just) Einstein (Back reaction of inhomogeneities)

Modifying the left-hand side

- Friedmann equation modified today — Freese & Lewis

$$H^2 = A\rho\left[1+\left(\rho/\rho_{\text{cutoff}}\right)^{n-1}\right]$$

- Gravitational force law modified at large distance — Deffayet, Dvali & Gabadadze
  Five-dimensional at cosmic distances
- Tired gravitons — Gregory, Rubakov & Sibiryakov; Dvali, Gabadadze & Porrati
  Gravitons metastable - leak into bulk
- Gravity repulsive at distance $R \approx$ Gpc — Csaki, Erlich, Hollowood & Terning
- $n=1$ KK graviton mode very light, $m \approx$ (Gpc)$^{-1}$ — Kogan, Mouslopoulos, Papazoglou, Ross & Santiago
- Backreaction of inhomogeneities — Räsänan; Kolb, Matarrese, Notari & Riotto; Notari; Kolb, Matarrese & Riotto

Braneless cosmology

Old Friedmann law:

$$G_{00} = M_{Pl}^{-2}\, T_{00}$$

$$3H^2 = M_{Pl}^{-2}\rho$$

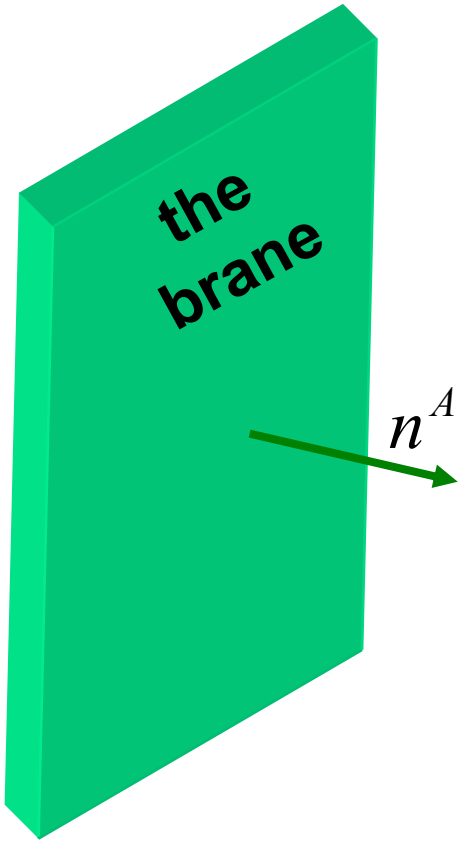
Friedmann (1921)

SNIa evidence for dark energy:

$$\int \frac{dz}{H(z)}$$

Brane cosmology

- Israel junction condition (Israel 1966)



- n^A : unit vector normal to the brane
- $h_{AB} = g_{AB} - n_A n_B$: the induced metric
- $\kappa_{AB} = h_A{}^C \nabla_C n_B$: the extrinsic curvature

$$\left[\kappa_{\mu\nu}\right] = -M_*^{-3} T_{\mu\nu}^{BRANE}$$

$[....]$ = discontinuity across the brane

$$a'' = \langle a'' \rangle + [a'] \delta(y)$$

discontinuity in second derivative of scale factor

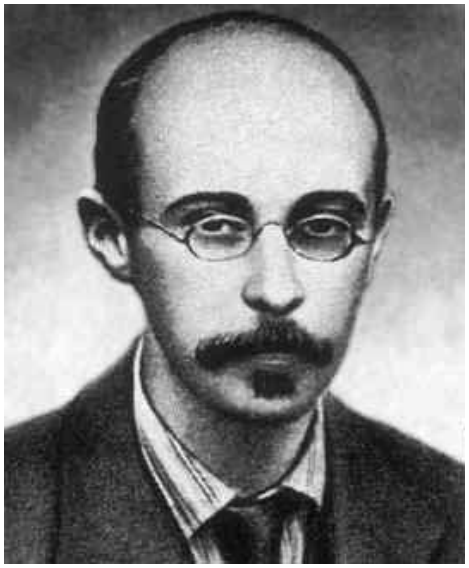
Braneless cosmology

Old Friedmann law:

$$G_{00} = M_{Pl}^{-2}\, T_{00}$$

$$3H^2 = M_{Pl}^{-2}\rho$$

Friedmann (1921)



SNIa evidence for dark energy:

$$\int \frac{dz}{H(z)}$$

Braneful cosmology

New Friedmann law:

Israel jump conditions

Binetruy, Deffayet, Langlois (2000)

$$3H^2 = \frac{\Lambda}{2} + \frac{M_*^{-6}}{12}\rho^2 + \frac{c}{a^4(t, y=0)}$$

Brane cosmology

- New Friedmann law Binetruy, Deffayet, Langlois (2000)

$$3H^2 = \frac{\Lambda}{2} + \frac{M_*^{-6}}{12}\rho^2 + \frac{c}{a^4(t, y=0)}$$

- Possible solution Randall & Sundrum (2000)

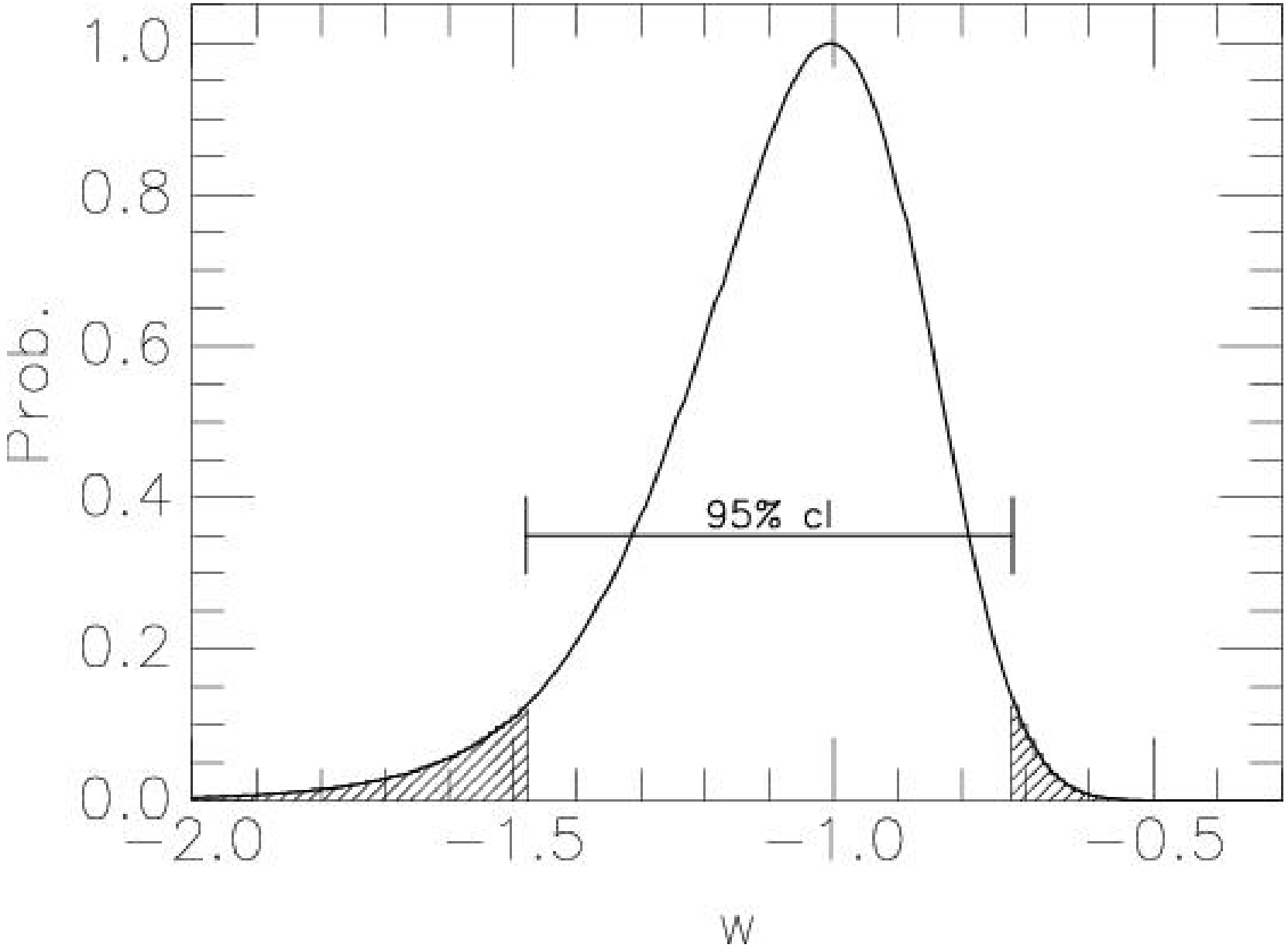
Introduce a tension σ on the brane $\rho \to \rho + \sigma$

$$3H^2 = \underbrace{\left(\frac{\Lambda}{2} + \frac{M_*^{-6}}{12}\sigma^2\right)}_{\text{cosmological constant (cancels?)}} + \underbrace{\frac{M_*^{-6}}{6}\sigma\rho}_{\frac{M_*^{-6}}{18}\sigma = \frac{8\pi G}{3}\ \text{Friedmann equation}} + \underbrace{\frac{M_*^{-6}}{12}\rho^2 + \frac{c}{a^4(t, y=0)}}_{\text{unconventional corrections}}$$

How do we sort it out?

- Something is established-ΛCDM too good to ignore
  - SNIa
  - Subtraction
  - Age
  - Large-scale structure
  - …..
- Is it "just" a cosmological constant? Is $w = -1$?
- If $w \neq -1$, what is the dynamics?

For now…parameterize



High-z supernova team

$w < -1$?

- **null dominant energy condition: energy doesn't propagate outside the light cone**

$$|p| \leq |\rho| \Rightarrow -\rho \leq p \leq \rho$$

- **model with $w < -1$: negative kinetic energy scalar field**

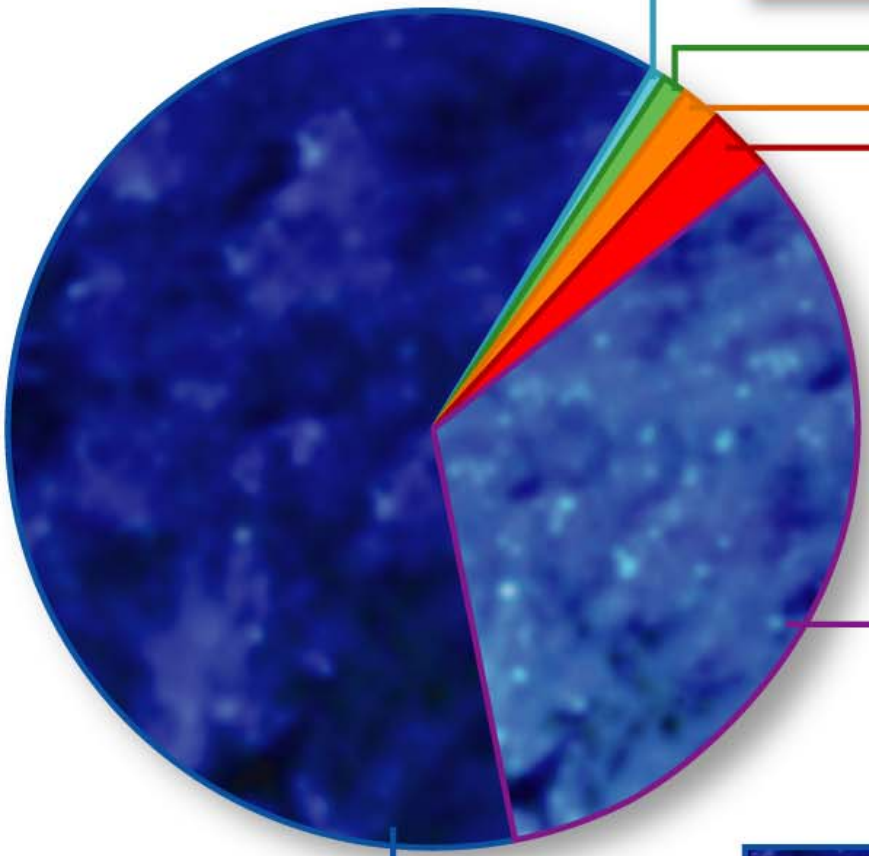
$$L = -\dot{\phi}^2 - \exp\left(-\phi^2\right)$$

- **instability cured with higher derivative terms?**

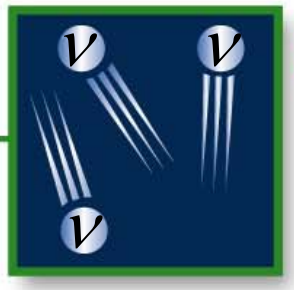
Aether of the 21st century?

- It's an infrared issue!
- It's an ultraviolet issue!

ΛCDM

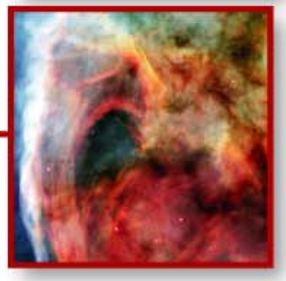


Chemical Elements:
(other than H & He) 0.03%

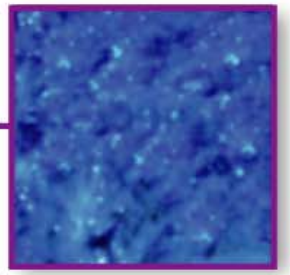


Neutrinos:
0.47%

Stars:
0.5%



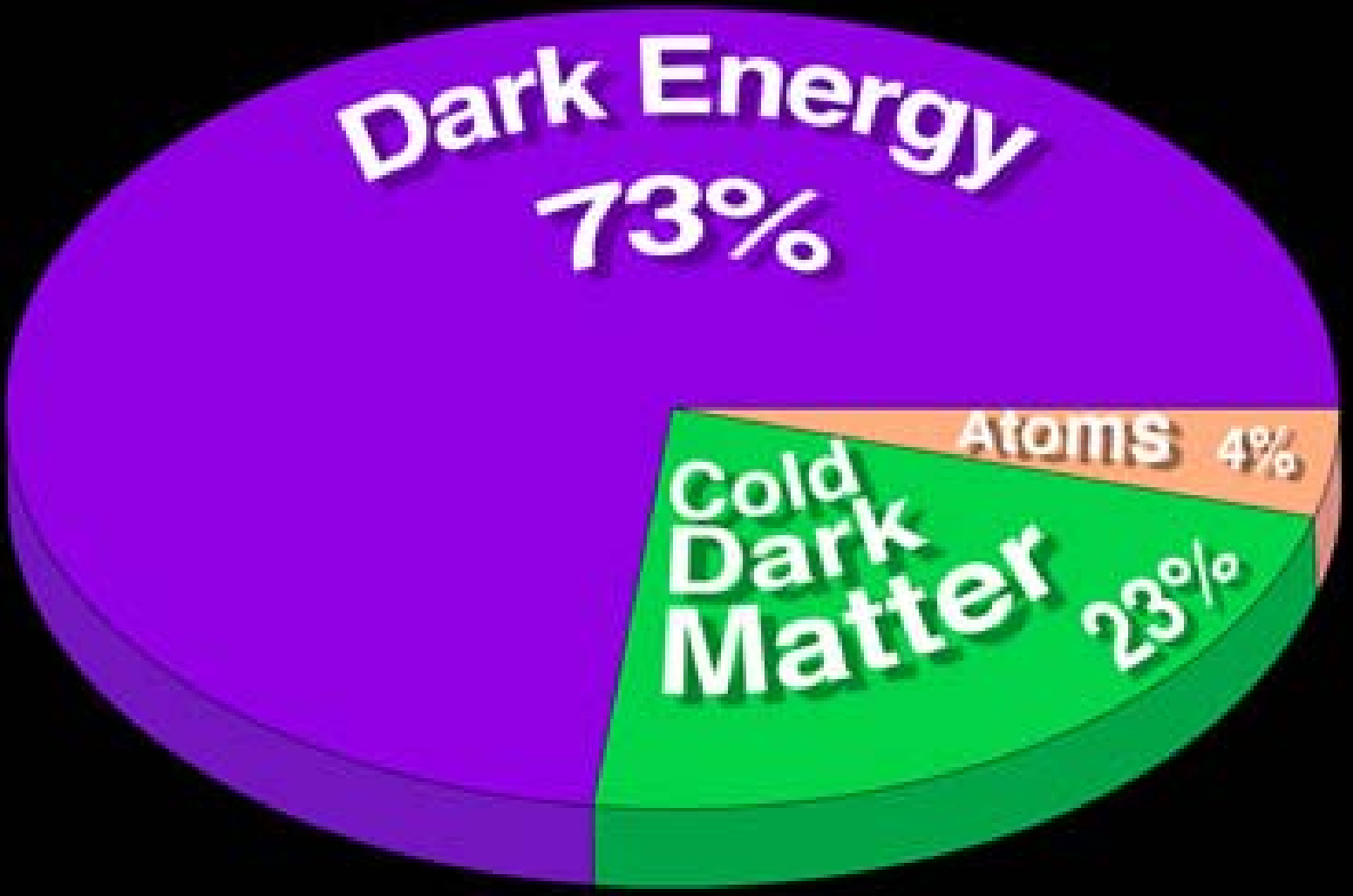
Free H
& He:
4%



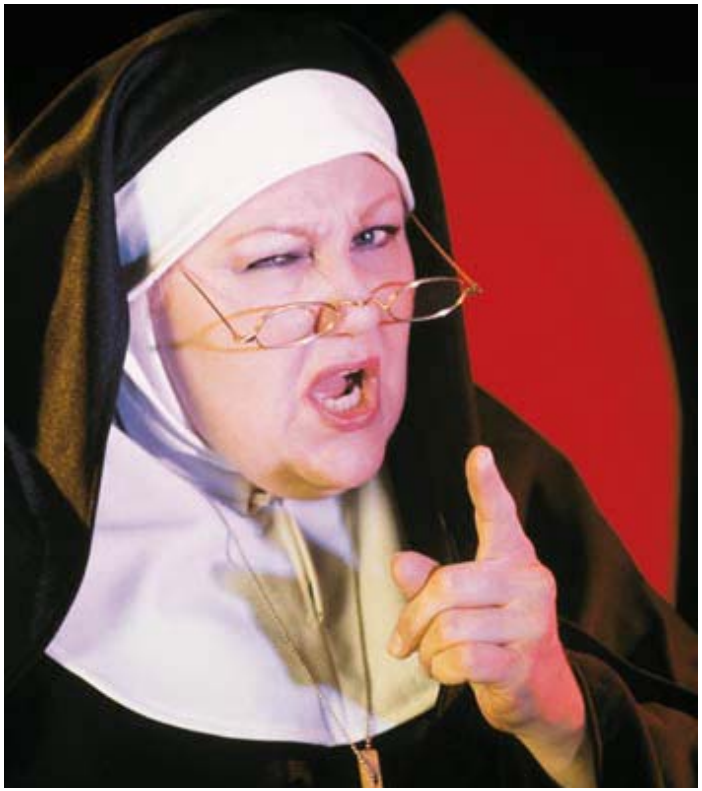
Dark Matter:
25%

Dark Energy:
70%

What we "know": ΛCDM

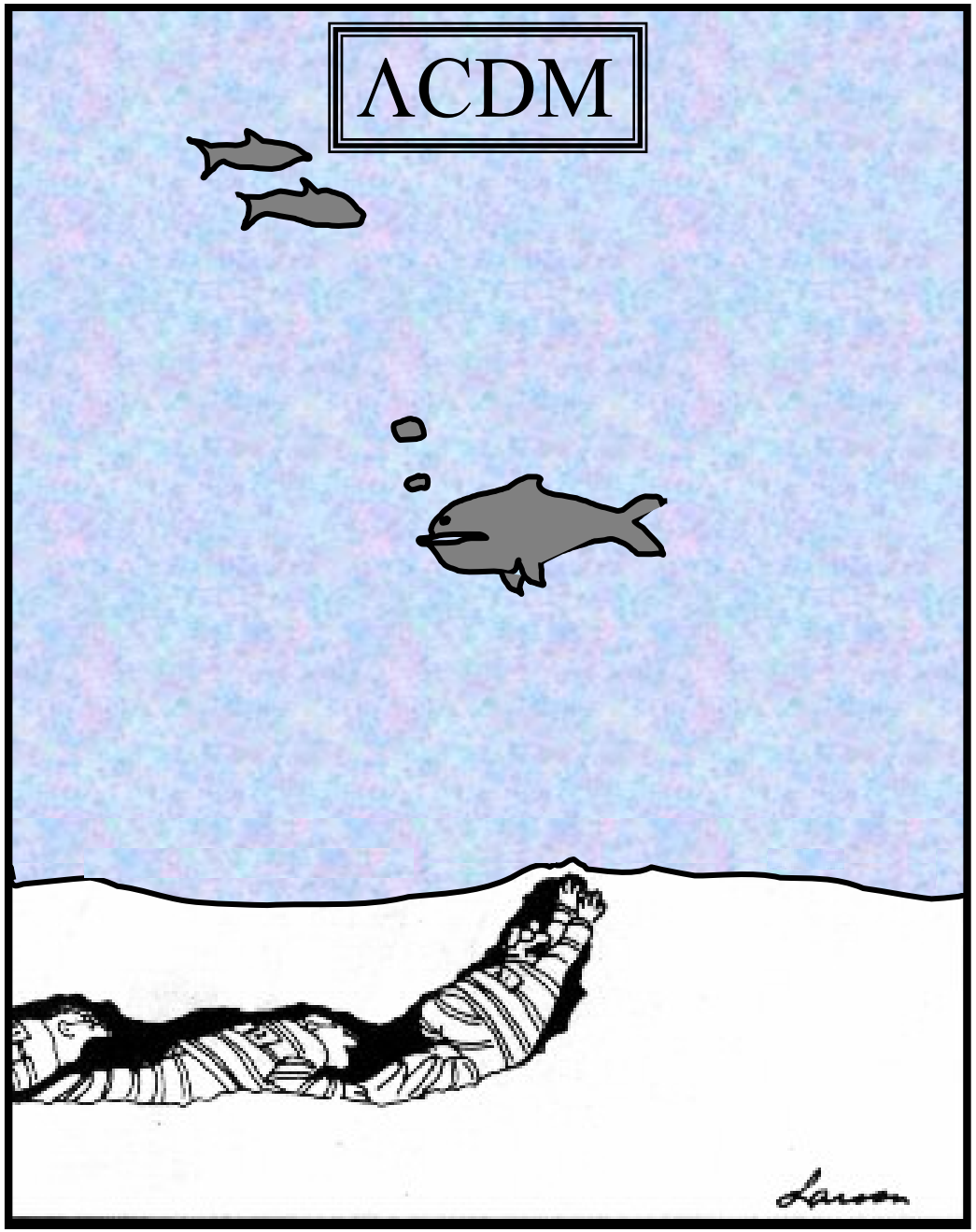


The importance of chastity



“Skepticism is the chastity of the intellect; it should not be surrendered too readily.”

– *G. Santayana*



We’re almost free, I just felt the first drops of rain

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Rocky I: Dark Energy

Rocky II: Dark Matter

Rocky Kolb
Fermilab & The University of Chicago